Identifying Reservoir Depletion Patterns with Applications to Seismic Imaging

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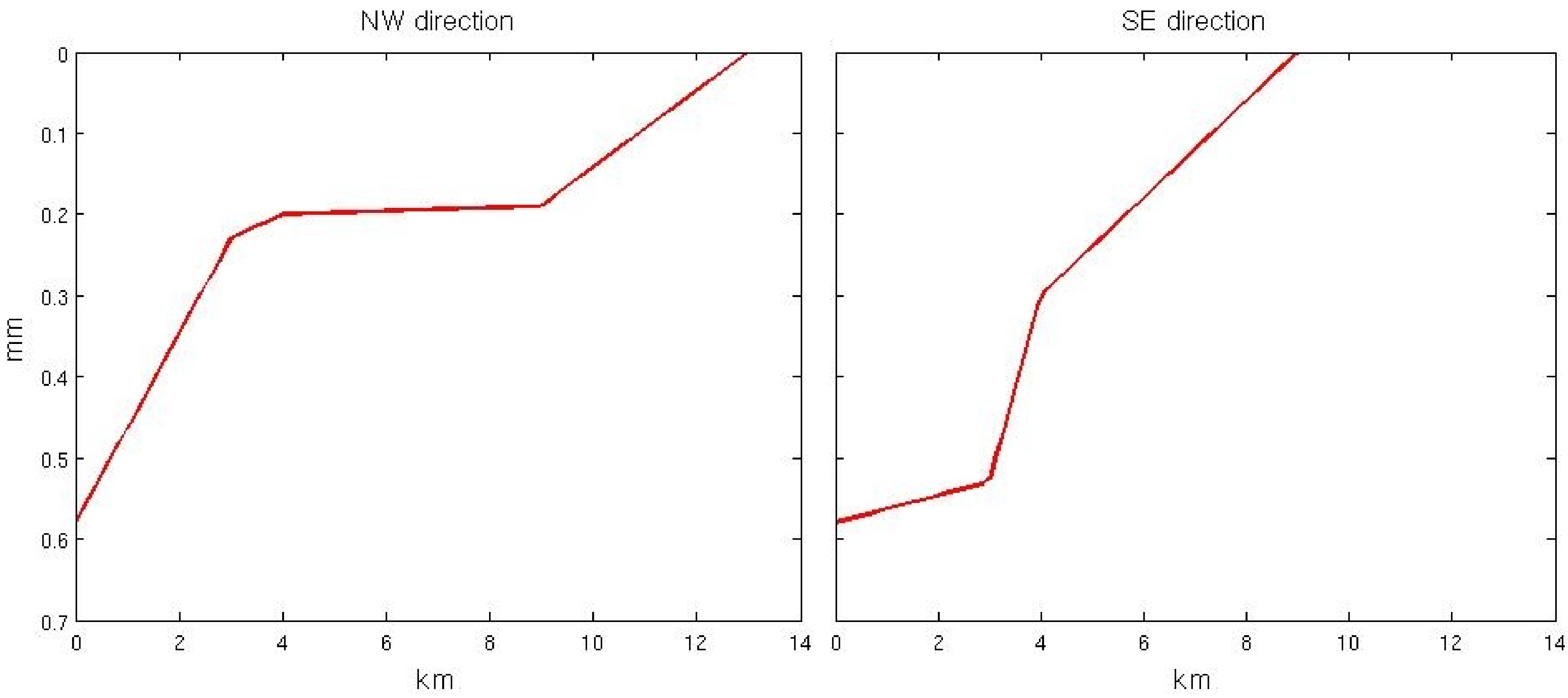
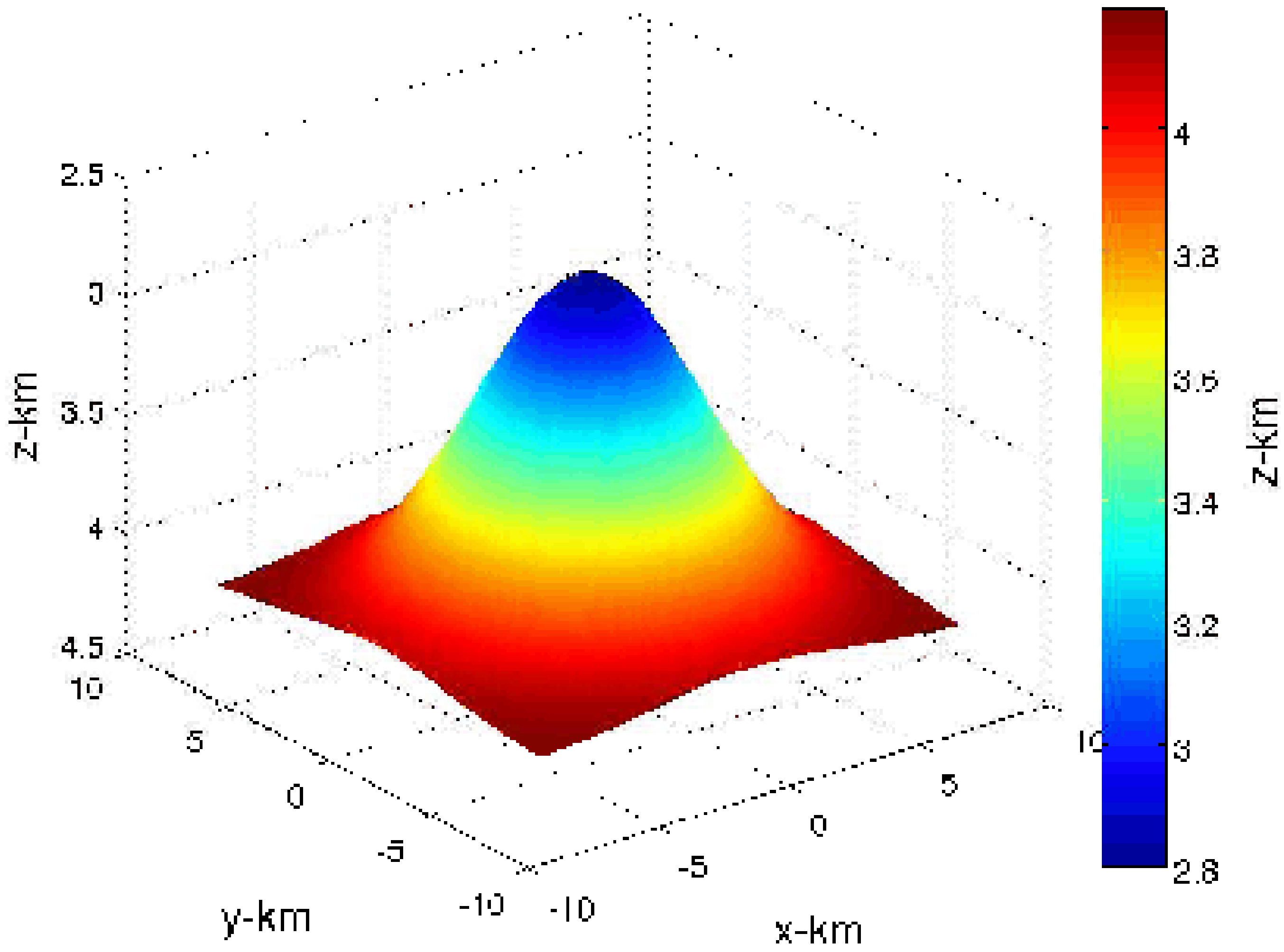
Origins

- The study originates in attempts to use geologic/ geomechanic constraints in seismic imaging.
- Can geologic/ geomechanic data be used for the regularization of e.g. least-squares migration to mitigate illumination artifacts?
  - acquisition-related illumination artifacts (YES!)
  - model-related illumination artifacts (unknown)
- Well tie-ins, steering filters (Clapp et al. 1997) can be used for the regularization of e.g. tomographic inversion. Beyond that, quantitative connections are controversial.
- What we don't do: Carcione et al. 2003, Kvam et al. 2005, Varela et al. 2006.

Lacq Subsidence (Segall et al. 1994)



Lacq Gas Reservoir



Objectives

- Develop a robust numerical technique for modeling displacements and inverting pore-pressure change for known blocky or layered poroelastic medium.
- Interpolate partial displacement data without detailed prior knowledge of poroelastic medium parameters.
- Generate time-lapse seismic data from strain-induced velocity updates (Hatchell, Bourne 2005) .
- Generate synthetic time-lapse data where monitor acquisitions have illumination gaps.

Quasistatic Poroelastic Model

$$\mu \nabla^2 u_i + \frac{\mu}{1-2\nu} \frac{\partial^2 u_j}{\partial x_i \partial x_j} = \alpha \frac{\partial p}{\partial x_i} - f_i$$

$$S_\alpha \frac{\partial p}{\partial t} - \frac{\kappa}{\eta} \nabla^2 p = -\alpha \frac{\partial}{\partial t} \nabla \cdot \boldsymbol{u}$$

- 4 equations for displacement and pore pressure change (*p*); *μ* is shear modulus, ***ν*** Poisson's ratio, *α* Biot coefficient, *κ* permeability, η fluid viscosity, *S* is the storage coefficient.

The Importance of Analytic Solutions

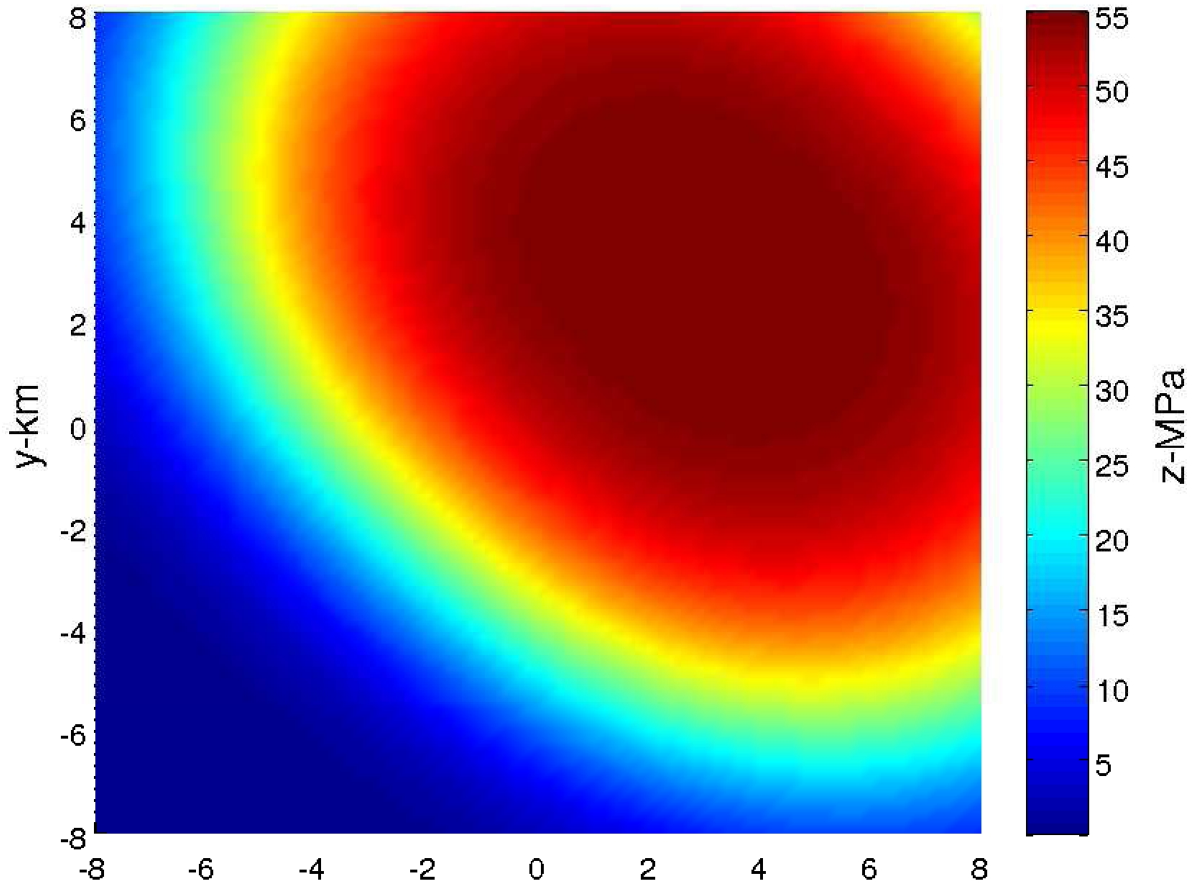
- Analytic Green's function for the fully-coupled system in half-space with a free boundary is unknown.
- We use fluid-to-solid coupling approximation where the elastostatic Green's tensor (Mindlin 1936) is used to generate displacement Green's tensor due to a concentrated dilatational force.
- Analytic solutions can be used to construct asymptotic solutions for slowly-varying or blocky models.
- Numeric evaluation of Green's tensor or a BVP solution would require e.g. finite elements – expensive, especially in an inversion framework.
- Alternative numeric techniques exist – e.g., Wang et al. 2003.

Modeling I

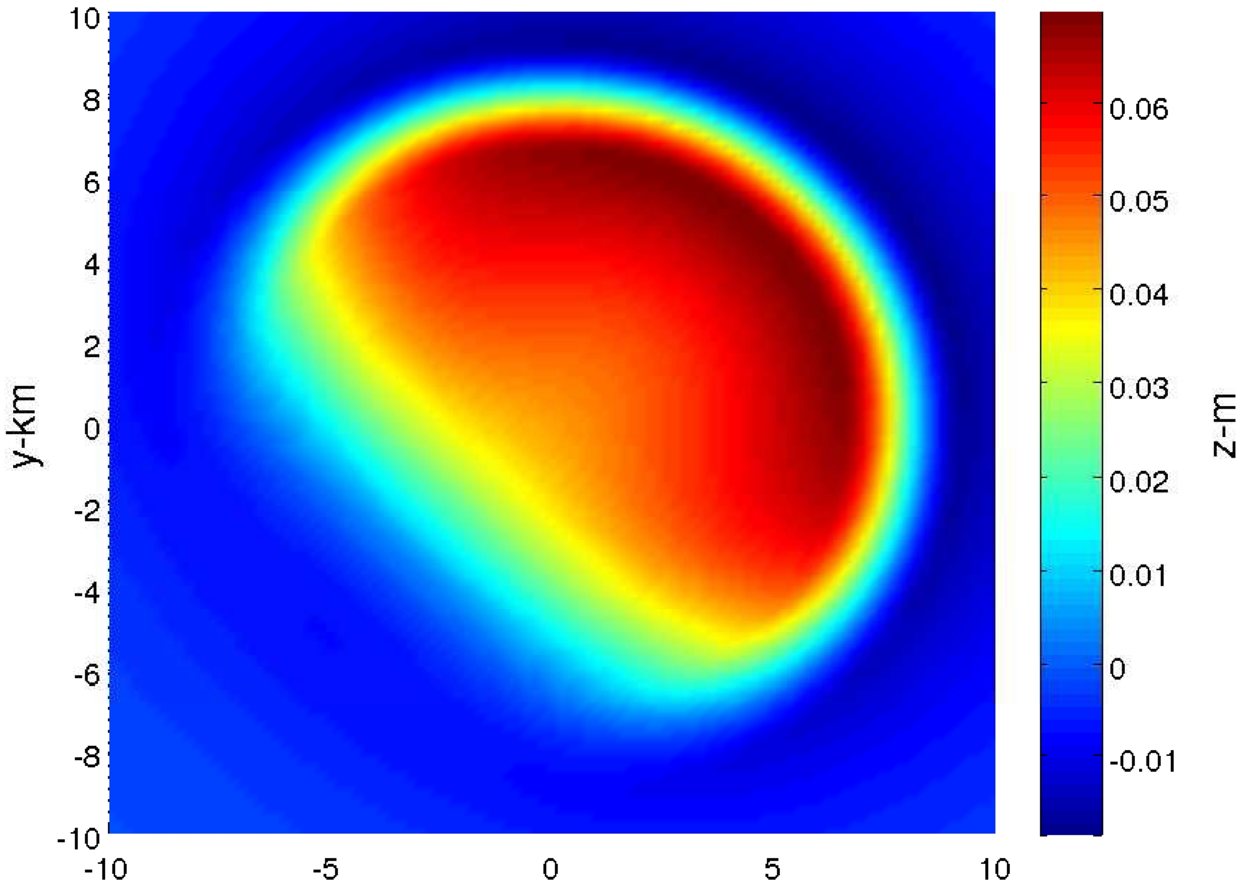
$$u_i(x,y,z)=\alpha\int_V h(\xi,\eta)\frac{\partial g_i^k(x,y,z,\xi,\eta,\zeta(\xi,\eta))}{\partial x_k}p(\xi,\eta,\zeta(\xi,\eta))\,d\xi\,d\eta$$

- where *g* is Mindlin's Elastostatic tensor (Segall et al. 94 use axisymmetric Green's tensor, we consider the general asymmetric case)

Asymmetric Pressure Drop Synthetic



Subsidence Modeling I

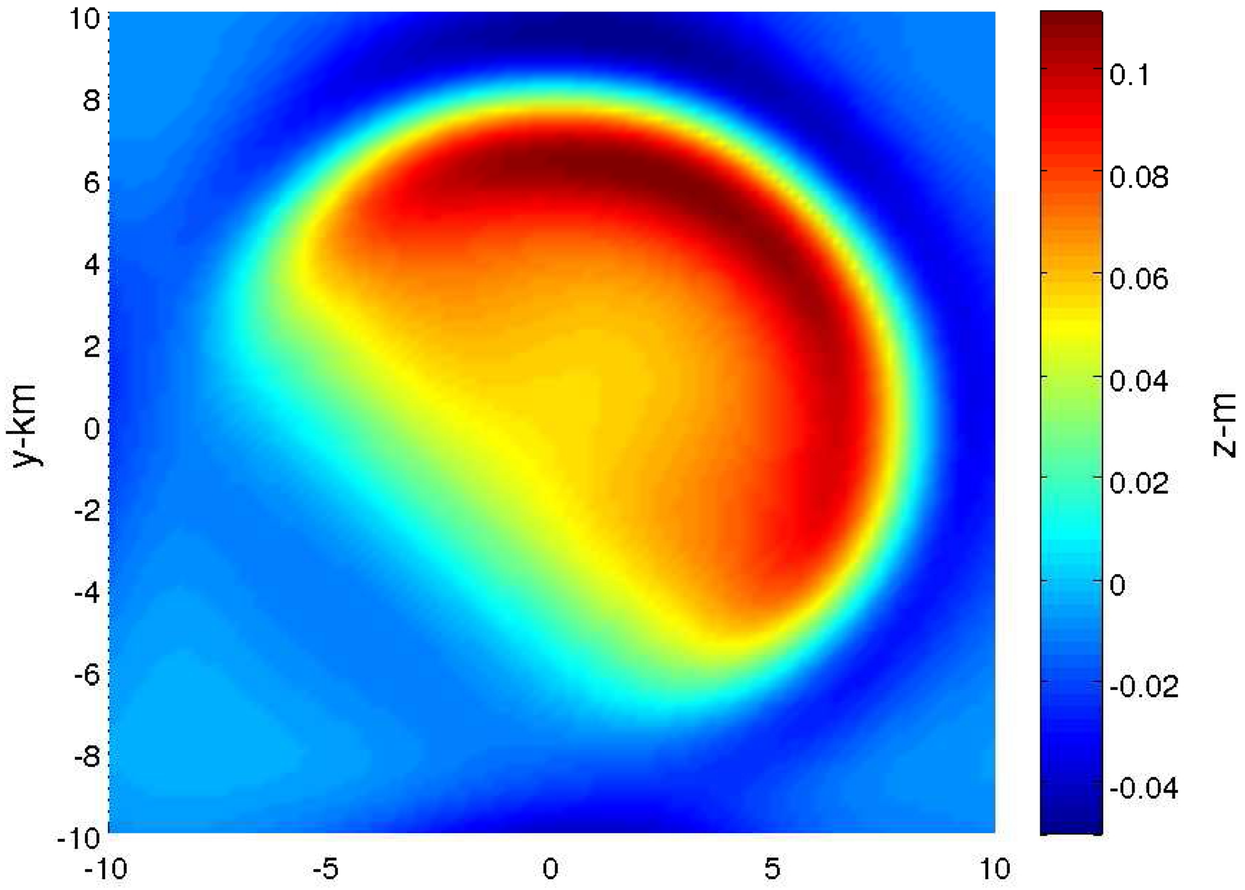


Modeling II

$$\mu \nabla^2 u_i + \frac{\mu}{1-2\nu} \frac{\partial^2 u_j}{\partial x_i \partial x_j} = -f_i$$

The pore pressure change is estimated right above the reservoir, and used to derive boundary conditions for the elastostatic system. The latter is solved by a parallelized 1D banded BVP solver for a layered or blocky model.

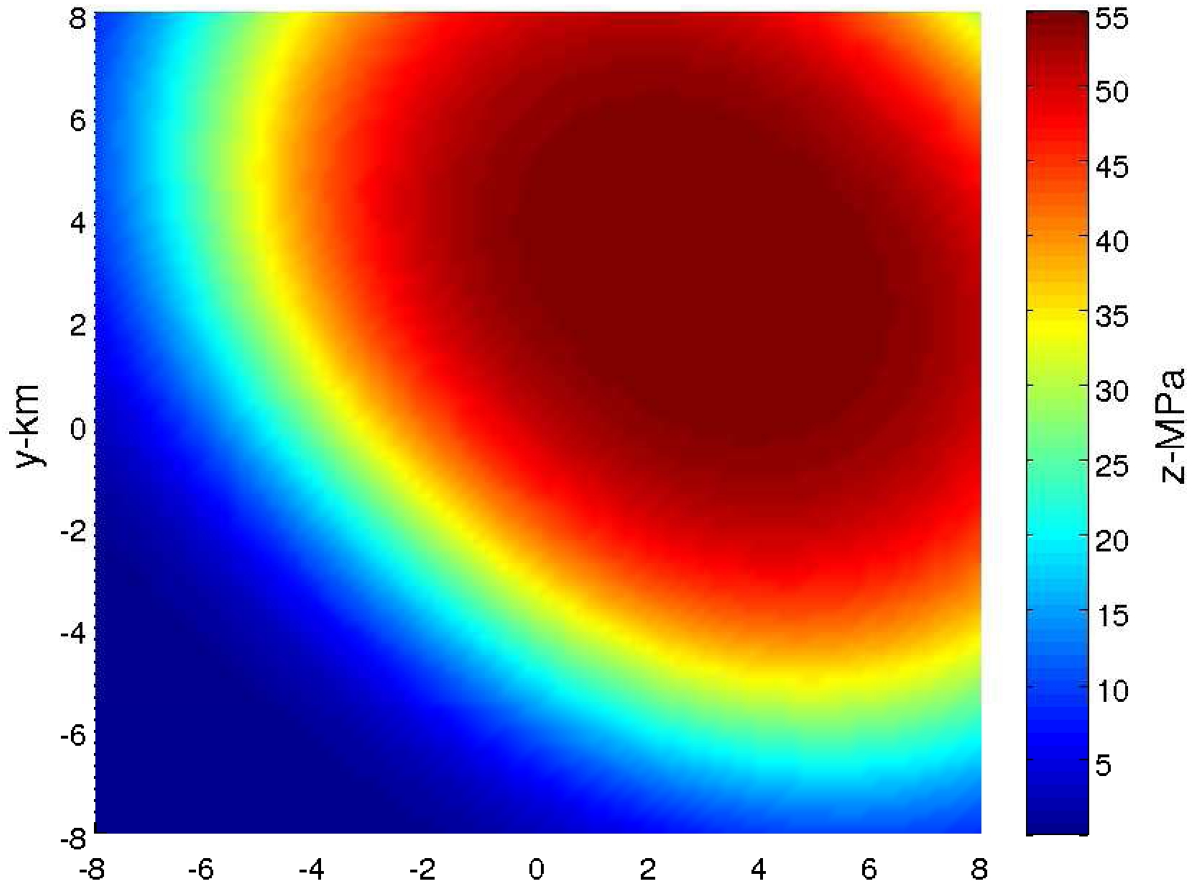
Subsidence Modeling II



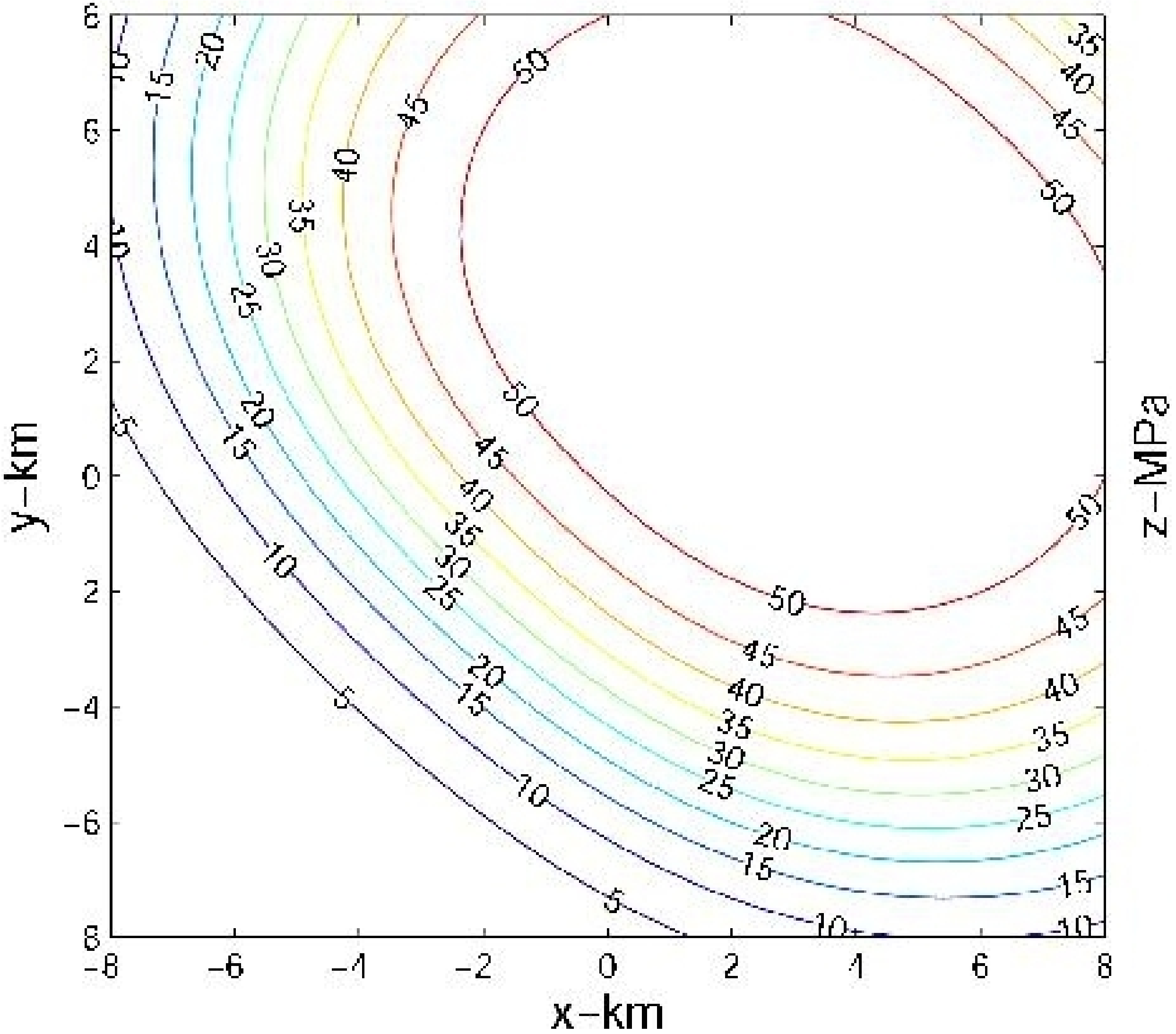
Inversion

- Numerically inverting the above integral transform is an ill-conditioned least squares problem.
- However, the underlying process is diffusive and multi-scale inversion can be easily applied.
- The output of inversion on a coarser grid is supplied as an initial approximation to inversion on a denser grid.
- Inversion of the simulated Lacq data is achieved within 4 iterations.
- Achieved robust inversion from only partial displacement data (e.g., only subsidence)

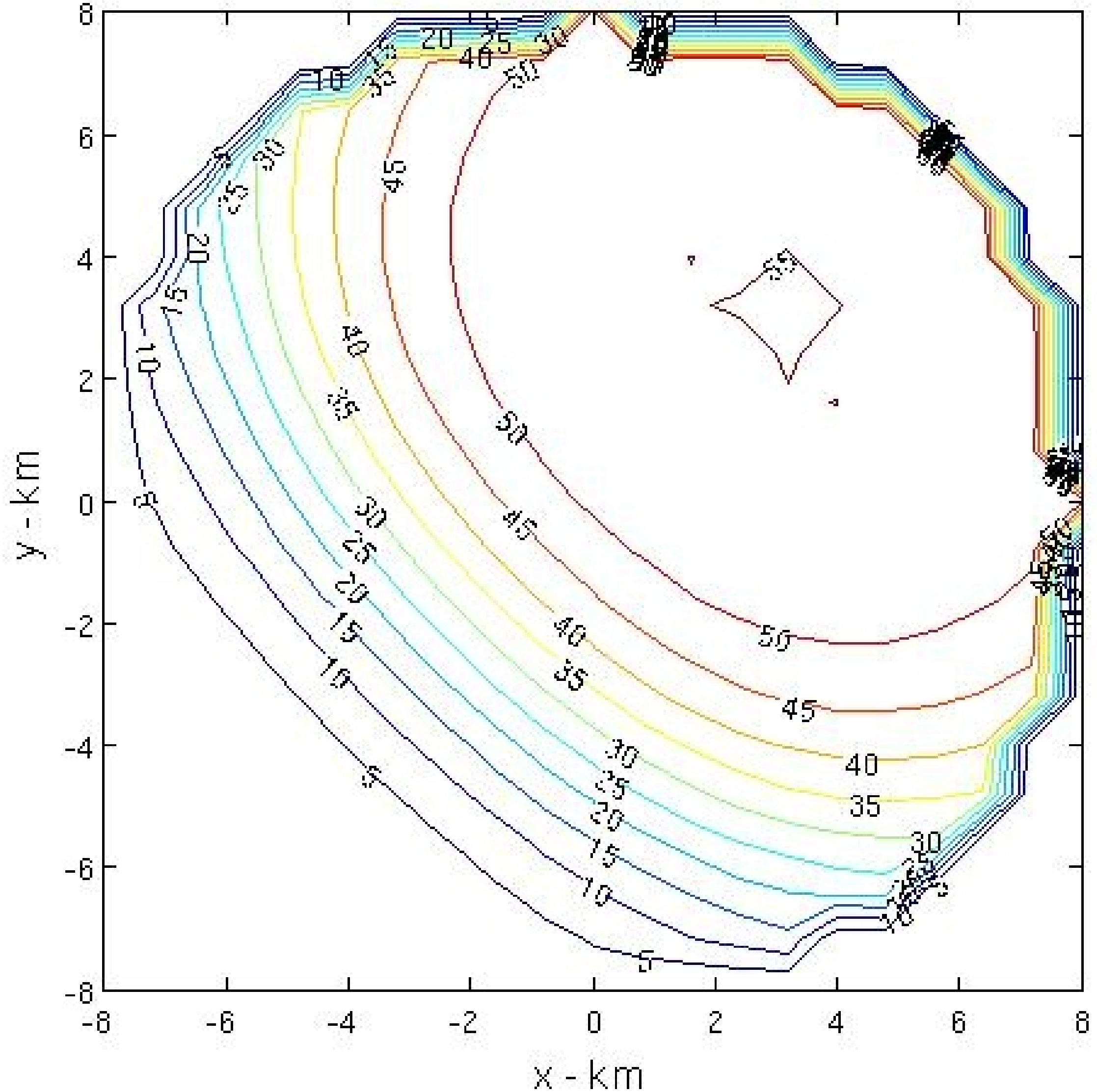
Application to Asymmetric Synthetic



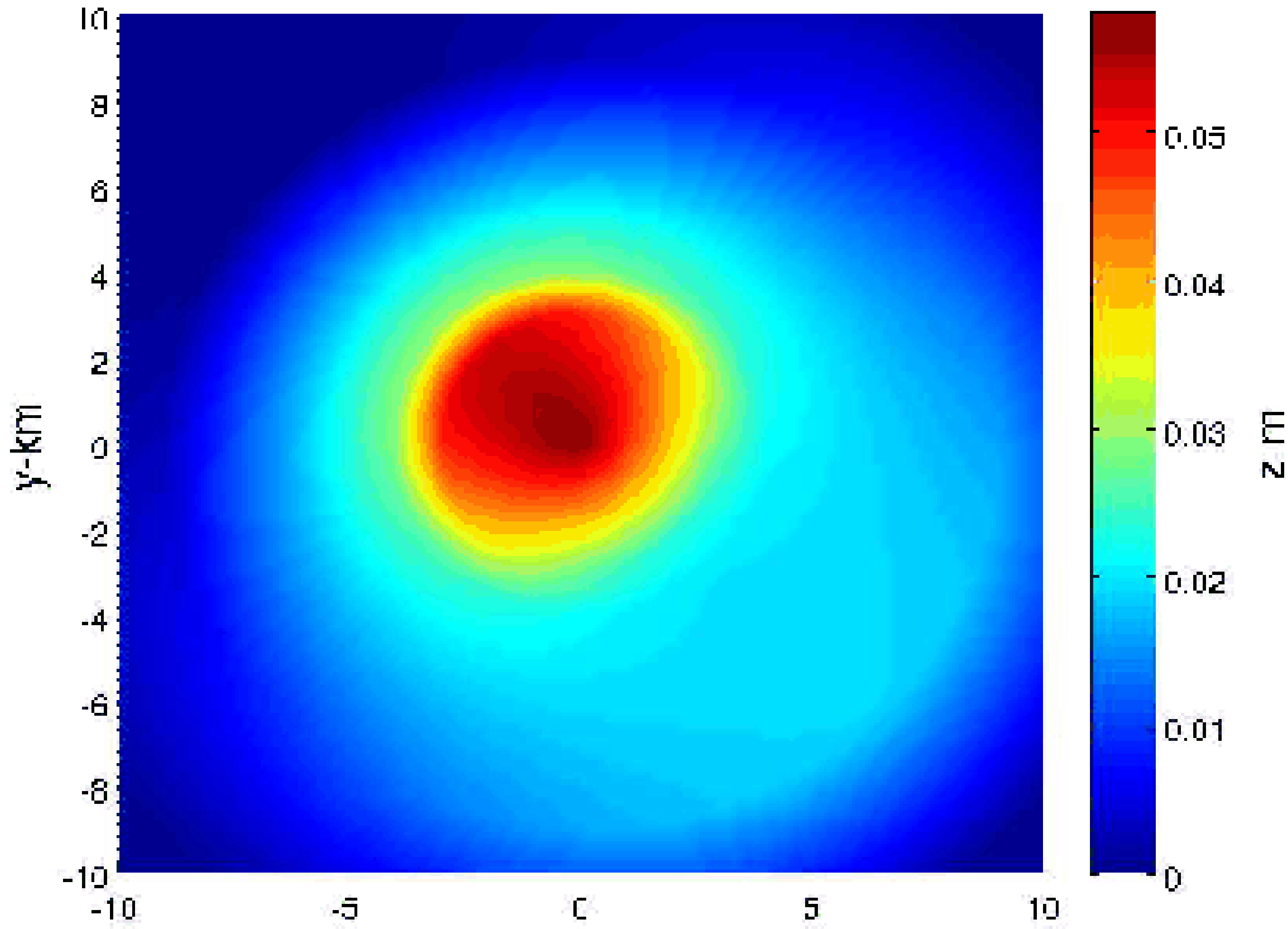
Application to Asymmetric Synthetic



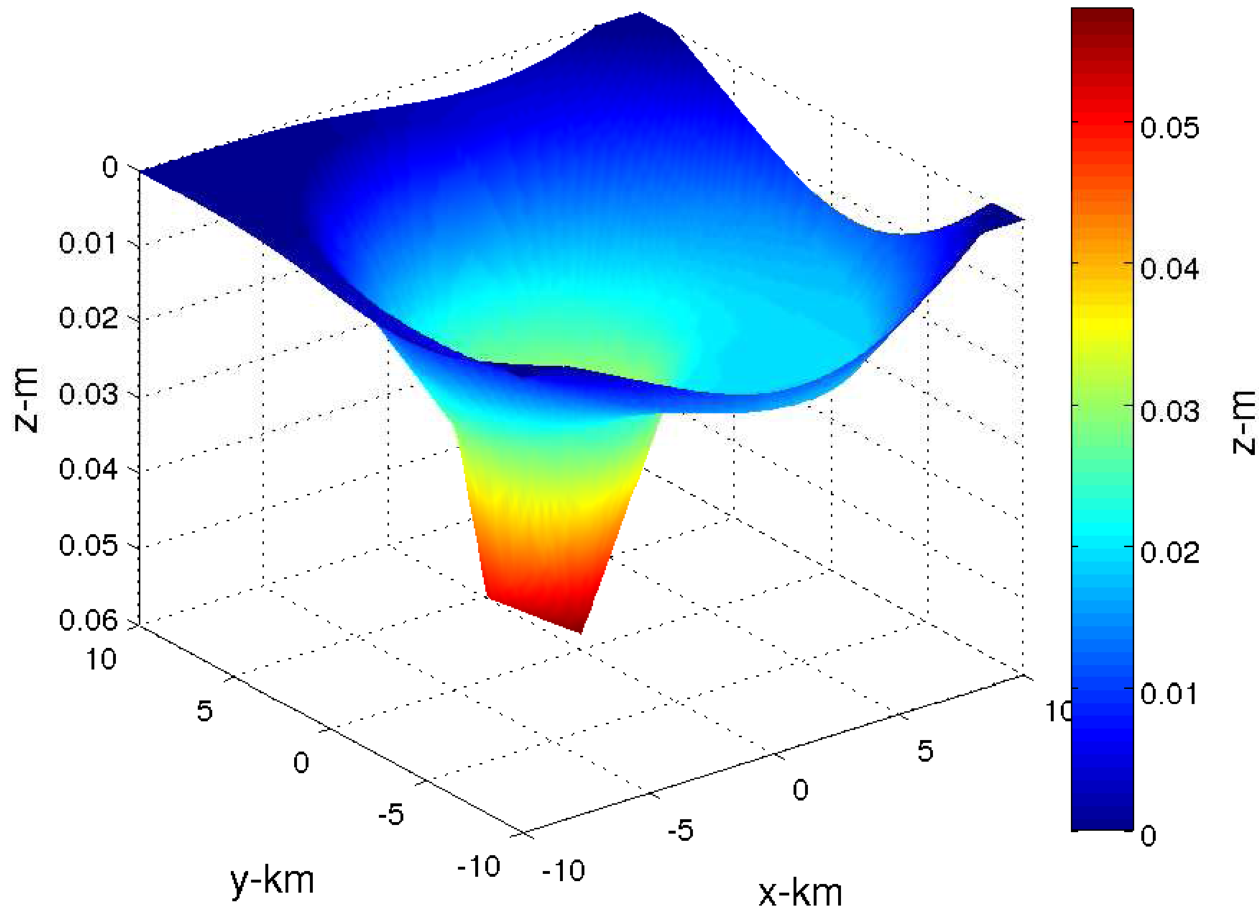
Application to Asymmetric Synthetic



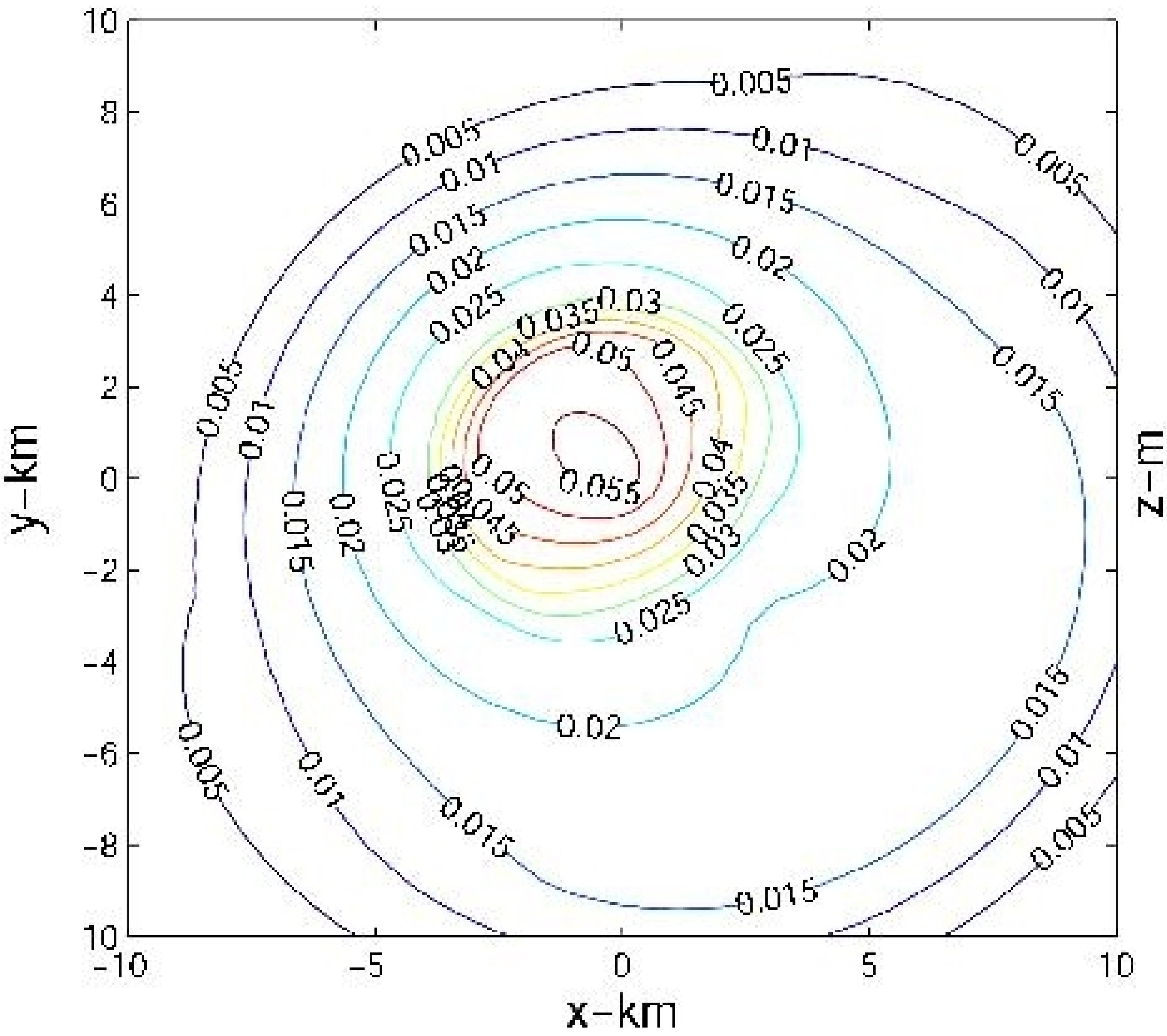
Application to Lacq Data - subsidence



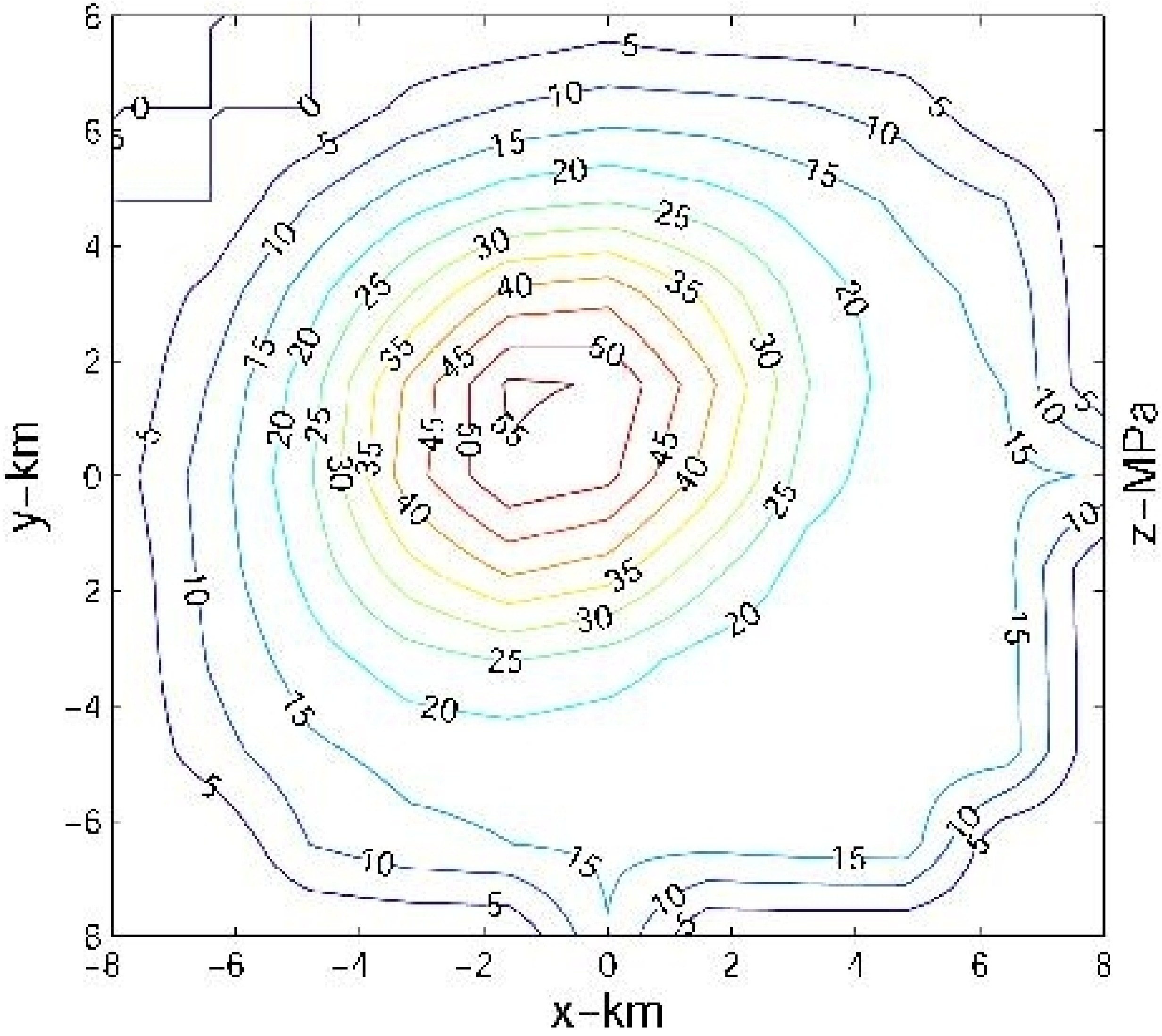
Application to Lacq Data - subsidence



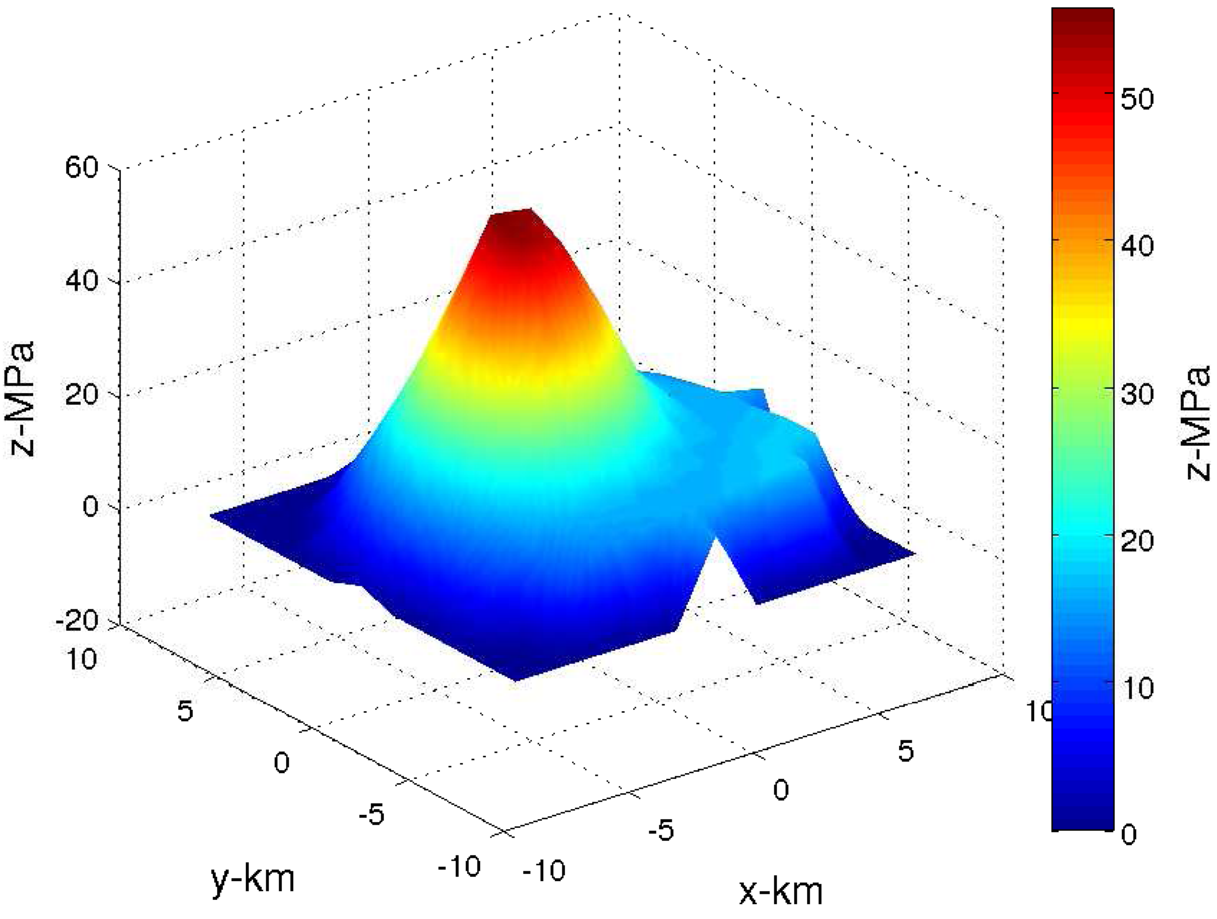
Application to Lacq Data - subsidence



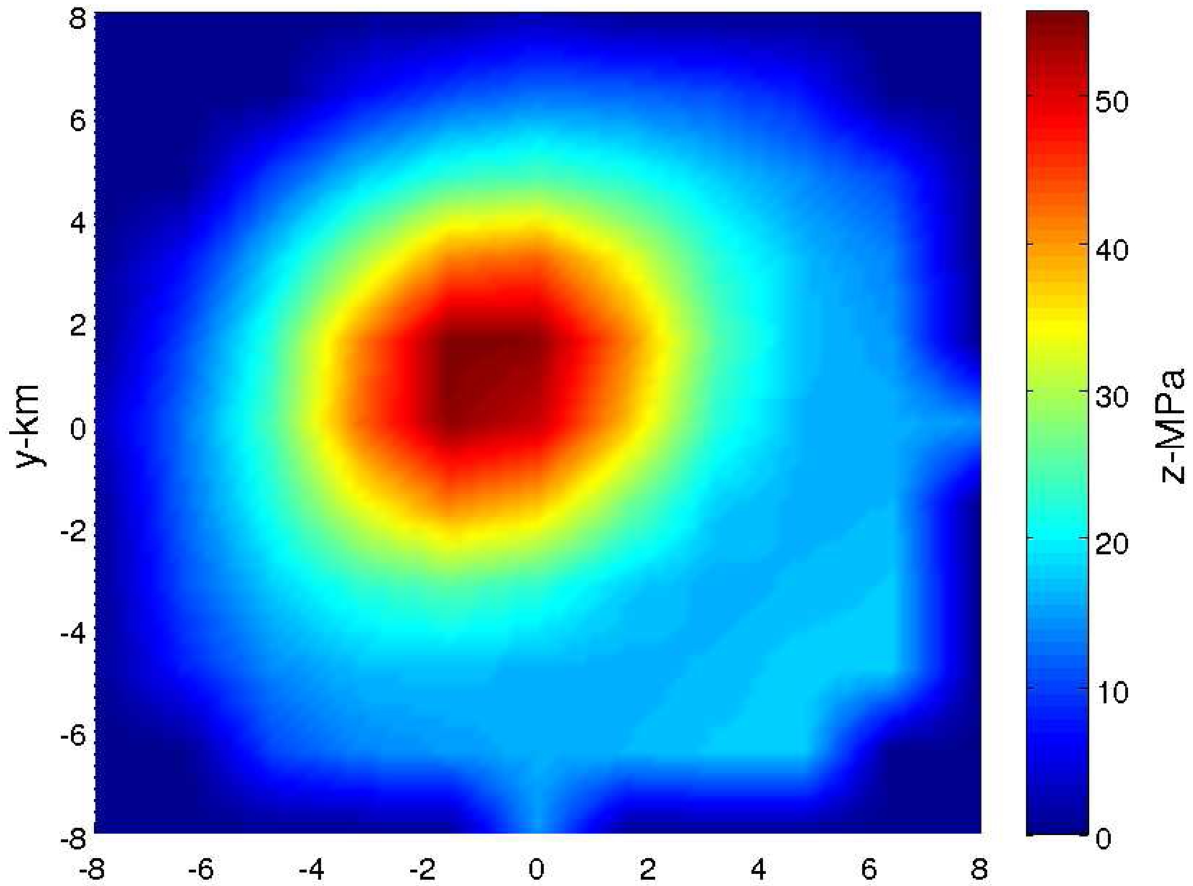
Application to Lacq Data – pp drop



Application to Lacq Data



Application to Lacq Data



exp_tk_*.* object-oriented framework

- EXPTK_INSTALL_DIR/exp_tk_*.*/src/tests/poroelastic_deform
- Modeling operators are implemented as classes (not procedure pointers) allowing a hierarchical implementation of poroelstic, elstoplastic and thermoelastic earth models – e.g, `poroelastic_green` extends `green_tensor`, `poroelastic_reservoir` extends `base_reservoir`, etc.
- Data structures are stored in header/binary files similar to SEP datasets but allowing arbitrary data geometry and distribution.
- The framework is 100% thread-safe, including data IO.
- No external dependencies except Intel Fortran >=12.0.

Velocity and density from deformation

$$\Delta\rho = -\rho\epsilon_{ii}$$

$$\frac{dV}{V} = -R\epsilon_{33}$$

$$\frac{dt}{t} = (1+R)\epsilon_{33}$$

(Hatchell and Bourne, 2005). Extract time-shifts using cross-correlation where available, estimate *R*, compute velocity change from deformation and *R*.

Conclusions and Perspectives

- Pore-pressure change can be inverted from only partial displacement data, suggesting a technique for Physics-based regularization of displacement interpolation.
- Application to real time-lapse seimic and subsidence data is required to validate the regularization approach.
- Blocky or slowly-varying models can be handled using asymptotic methods.
- Pseudo-differential operator factorization of the elastodynamic equations proposed in this work has resulted in the development of a computationally efficient one-way multicomponent elastic wave extrapolation method (SEP148).

Acknowledgments

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